Earth System Observations and Analysis

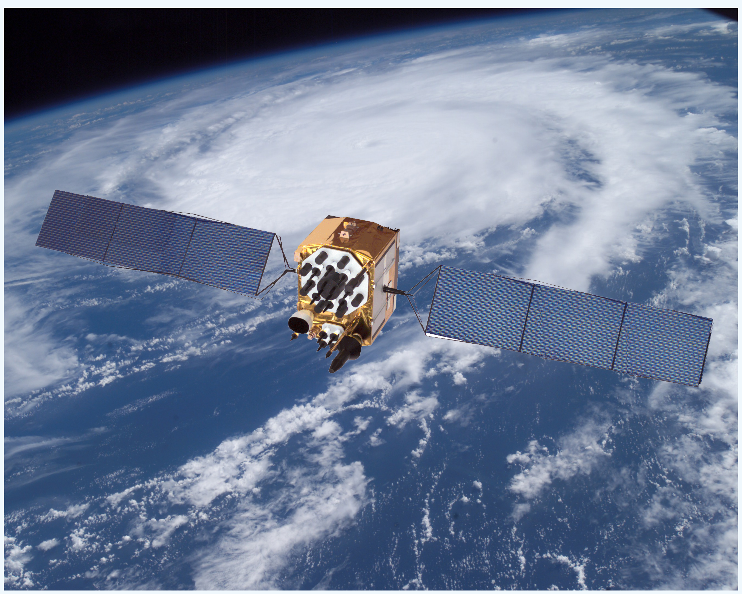
Earth System Research Laboratory

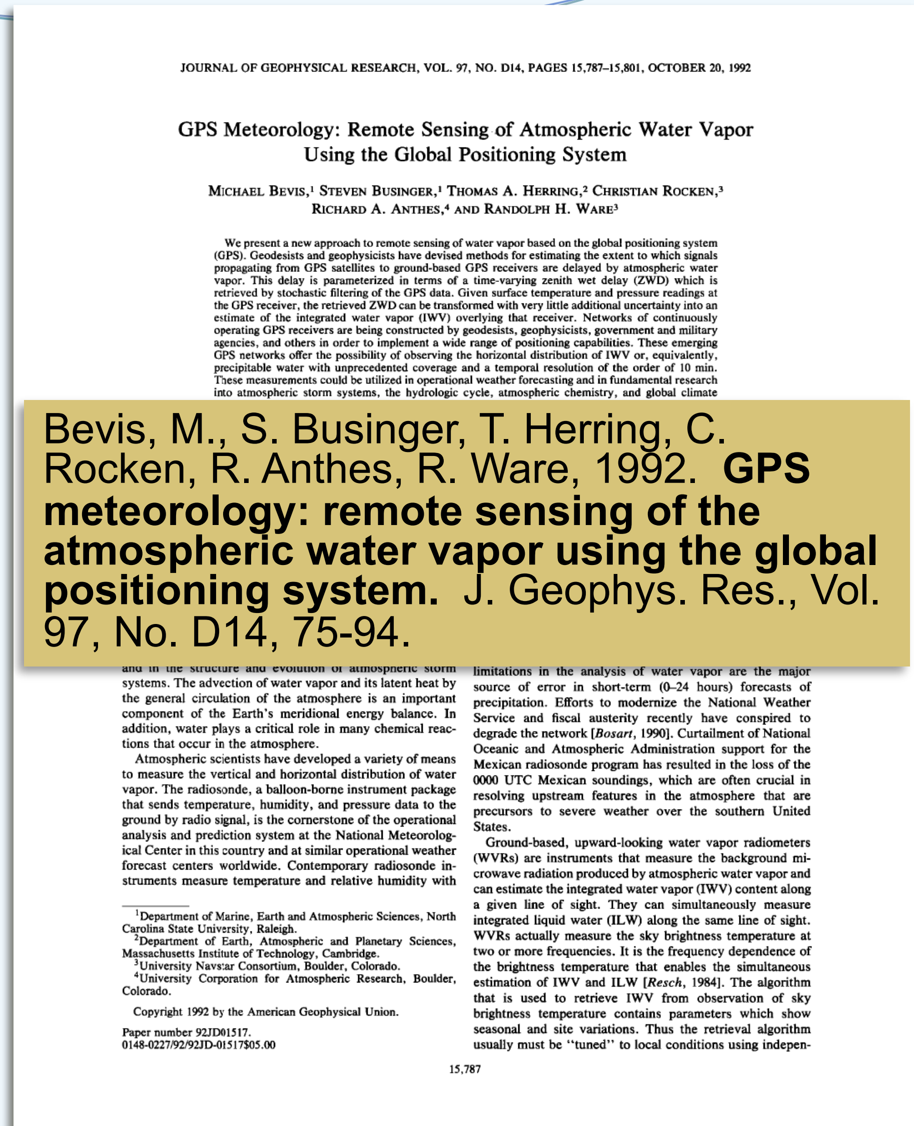
Seth I. Gutman

GPS Contributions to Operational Meteorology and Research

Background

- In the early 1990's, the atmos-pheric science community was looking for better ways to monitor water vapor.
- One promising candidate utilized the radio signals broadcast by the GPS satellites.





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GPS Meteorology: Remote Sensing of Atmospheric Water Vapor Using the Global Positioning System

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We present a new approach to remote sensing of water vapor based on the global positioning system (GPS). Geodesists and geophysicists have devised methods for estimating the extent to which signals propagating from GPS satellites to ground-based GPS receivers are delayed by atmospheric water vapor. This delay is parameterized in terms of a time-varying zenith wet delay (ZWD) which is retrieved by stochastic filtering of the GPS data. Given surface temperature and pressure readings at the GPS receiver, the retrieved ZWD can be transformed with very little additional uncertainty into an estimate of the integrated water vapor (IWV) overlying that receiver. Networks of continuously operating GPS receivers are being constructed by geodesists, geophysicists, government and military agencies, and others in order to implement a wide range of positioning capabilities. These emerging GPS networks offer the possibility of observing the horizontal distribution of IWV or, equivalently, precipitable water with unprecedented coverage and a temporal resolution of the order of 10 min. These measurements could be utilized in operational weather forecasting and in fundamental research into atmospheric storm systems, the hydrologic cycle, atmospheric chemistry, and global climate

and in the structure and evolution of atmospheric storm systems. The advection of water vapor and its latent heat by the general circulation of the atmosphere is an important component of the Earth's meridional energy balance. In addition, water plays a critical role in many chemical reactions that occur in the atmosphere.

Atmospheric scientists have developed a variety of means to measure the vertical and horizontal distribution of water vapor. The radiosonde, a balloon-borne instrument package that sends temperature, humidity, and pressure data to the ground by radio signal, is the cornerstone of the operational analysis and prediction system at the National Meteorological Center in this country and at similar operational weather forecast centers worldwide. Contemporary radiosonde instruments measure temperature and relative humidity with

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limitations in the analysis of water vapor are the major source of error in short-term (0–24 hours) forecasts of precipitation. Efforts to modernize the National Weather Service and fiscal austerity recently have conspired to degrade the network [*Bosart*, 1990]. Curtailment of National Oceanic and Atmospheric Administration support for the Mexican radiosonde program has resulted in the loss of the 0000 UTC Mexican soundings, which are often crucial in resolving upstream features in the atmosphere that are precursors to severe weather over the southern United States.

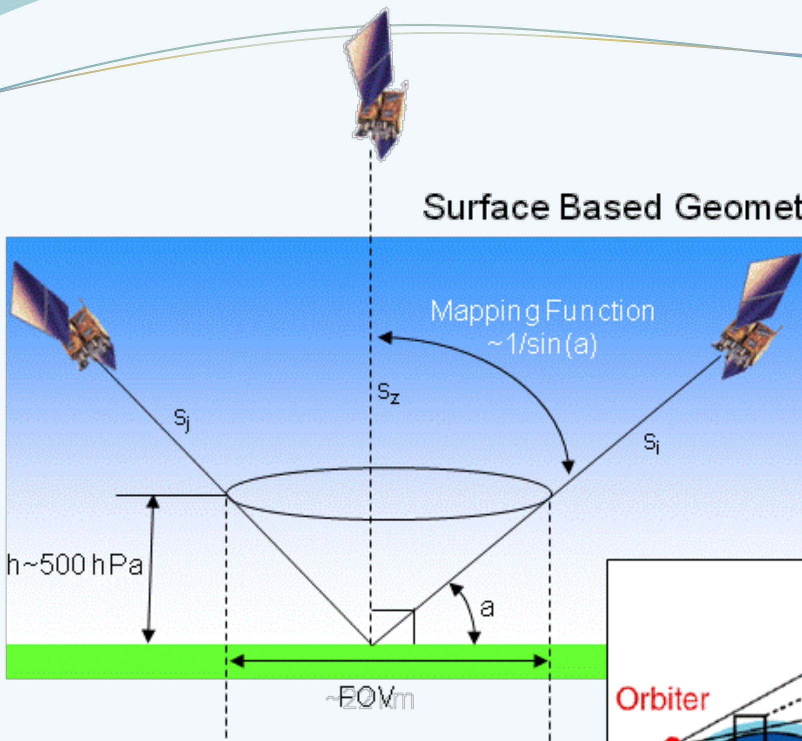
Ground-based, upward-looking water vapor radiometers (WVRs) are instruments that measure the background microwave radiation produced by atmospheric water vapor and can estimate the integrated water vapor (IWV) content along a given line of sight. They can simultaneously measure integrated liquid water (ILW) along the same line of sight. WVRs actually measure the sky brightness temperature at two or more frequencies. It is the frequency dependence of the brightness temperature that enables the simultaneous estimation of IWV and ILW [*Resch*, 1984]. The algorithm that is used to retrieve IWV from observation of sky brightness temperature contains parameters which show seasonal and site variations. Thus the retrieval algorithm usually must be "tuned" to local conditions using indepen-

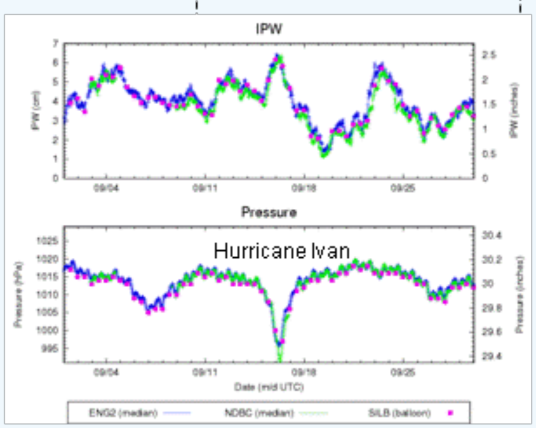
15,787

Bevis, M., S. Businger, T. Herring, C. Rocken, R. Anthes, R. Ware, 1992. **GPS meteorology: remote sensing of the atmospheric water vapor using the global positioning system.** J. Geophys. Res., Vol. 97, No. D14, 75-94.

GPS Observations in Meteorology

Surface Based Geometry





In both cases, the fundamental measurement is

$$\Delta s = 10^{-6} \int N(s)ds$$

N(s) the refractivity of the atmosphere along the path of the radio signal $N(s) = 10^{6} (n(s)-1)$.

Space Based Geometry

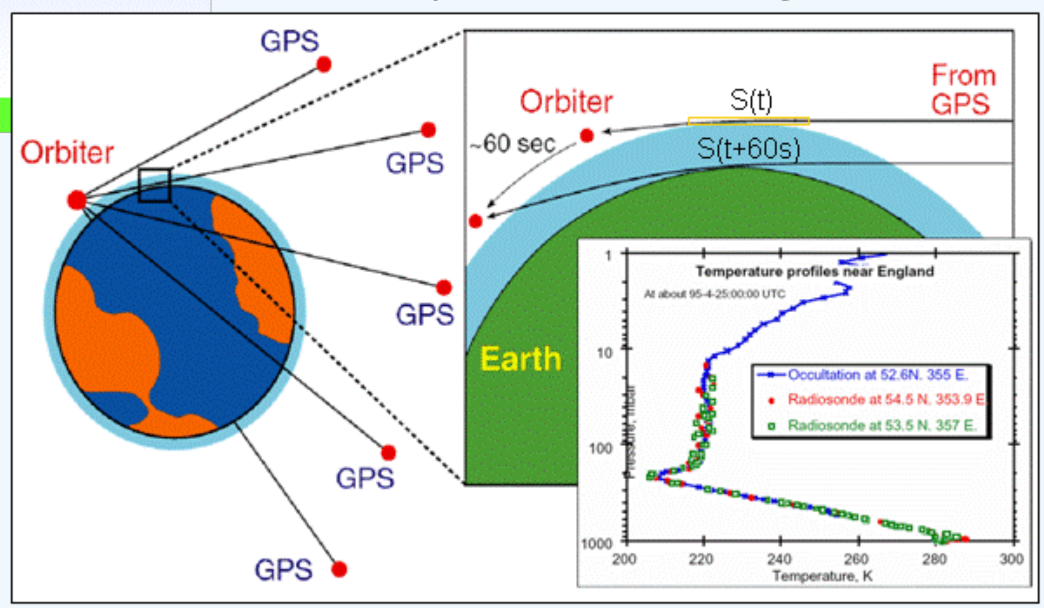
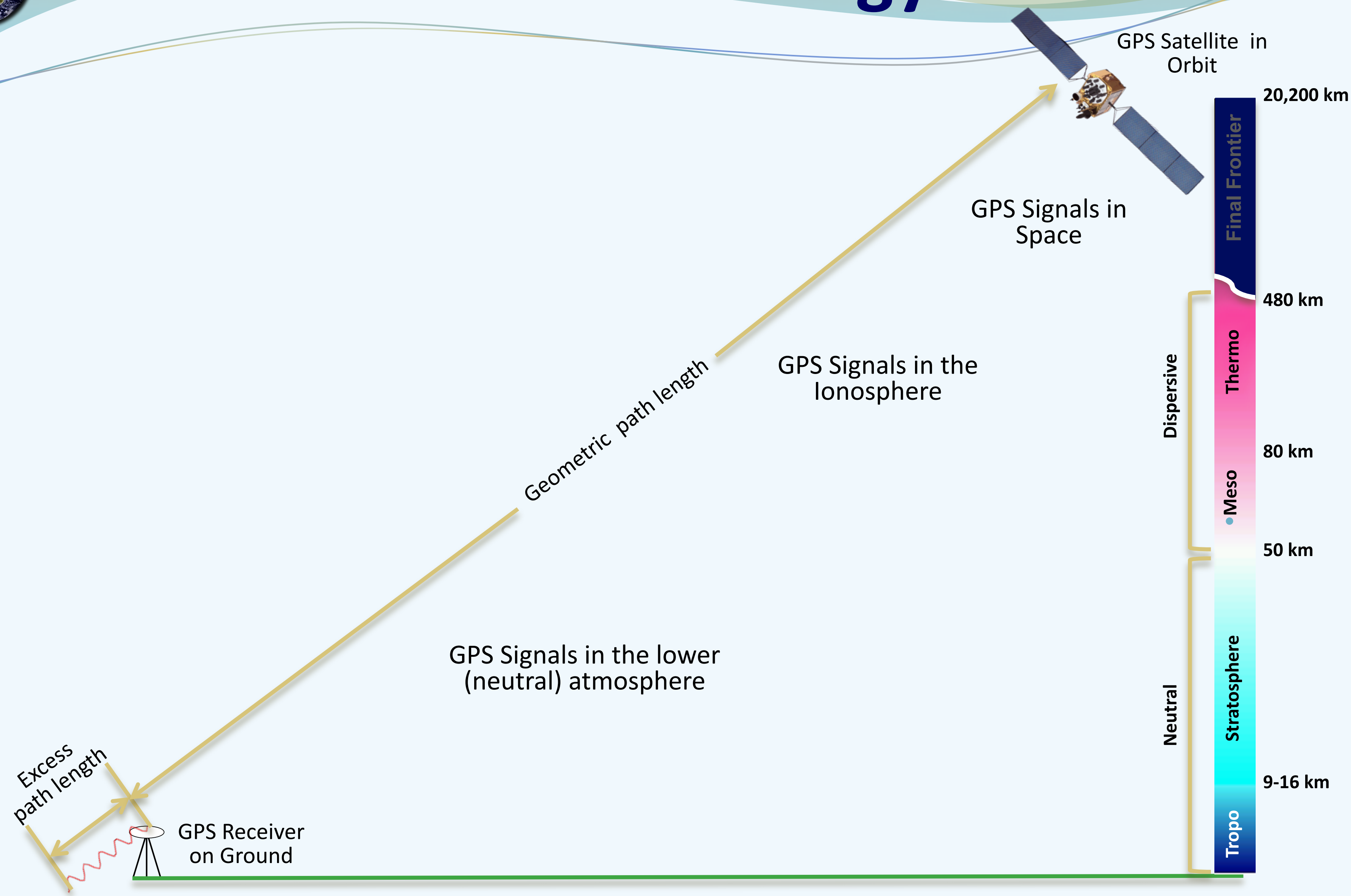
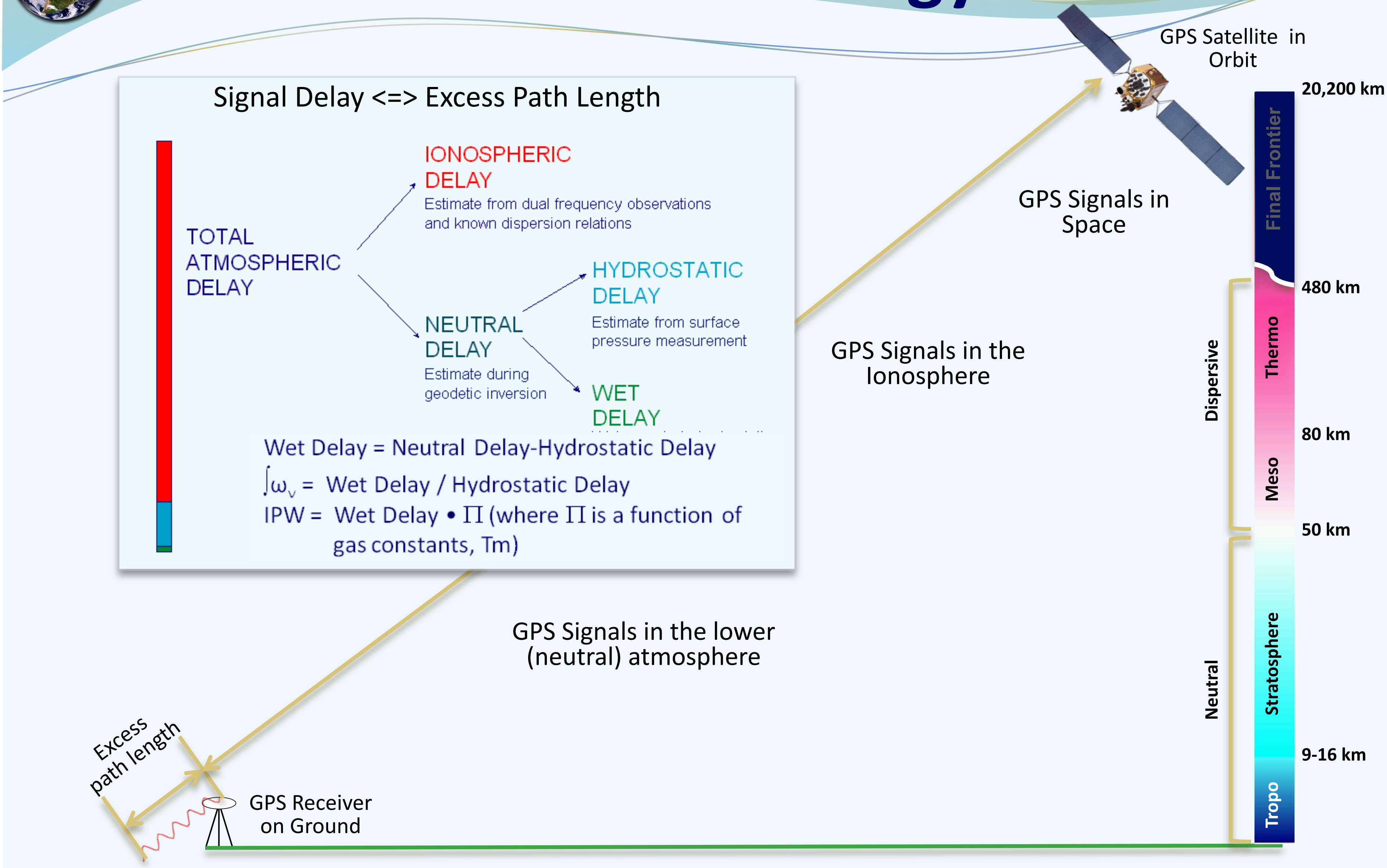


Illustration above courtesy of T. Yunk, NASA JPL.

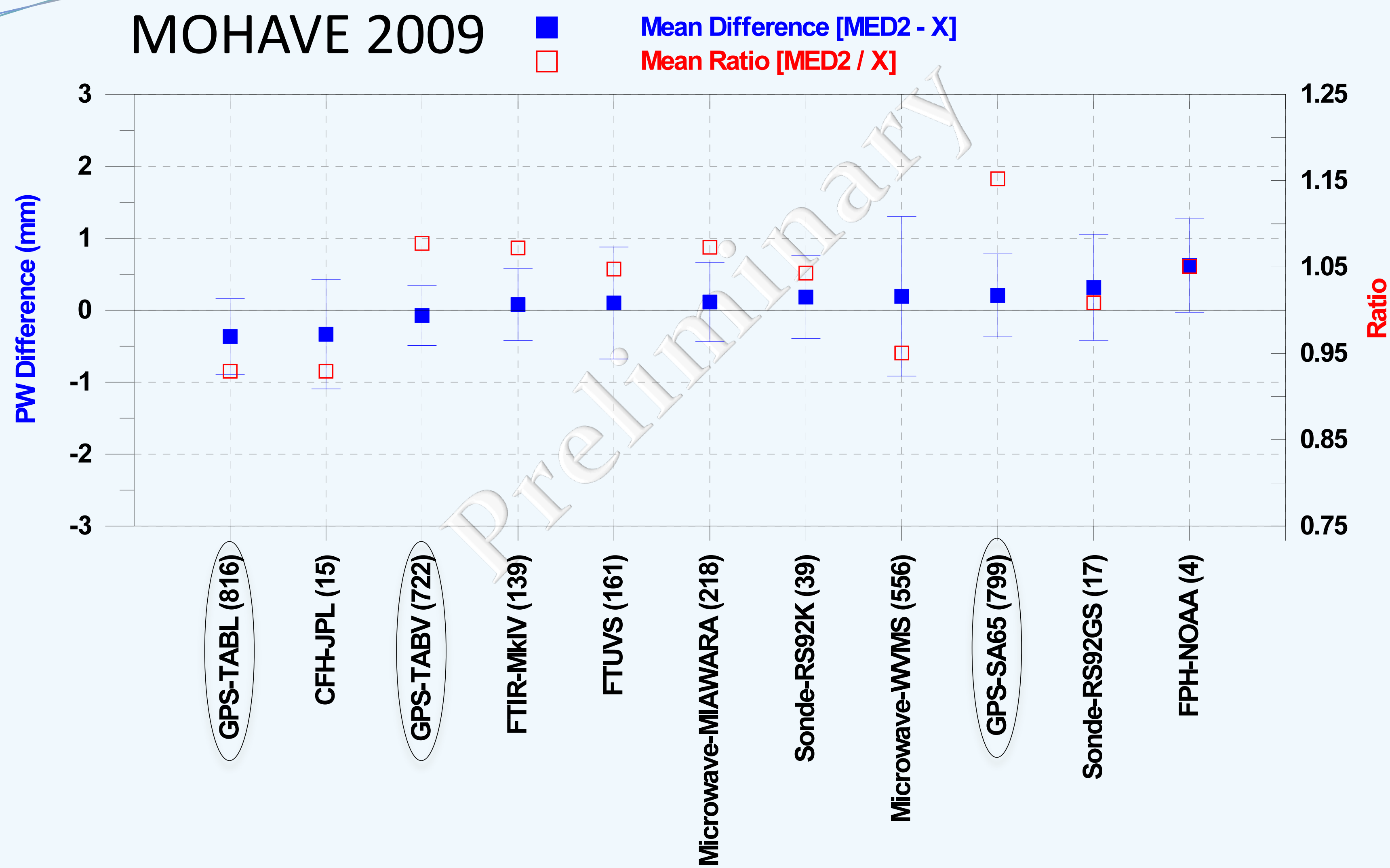
GPS Meteorology



GPS Meteorology



GPS IPW Accuracy



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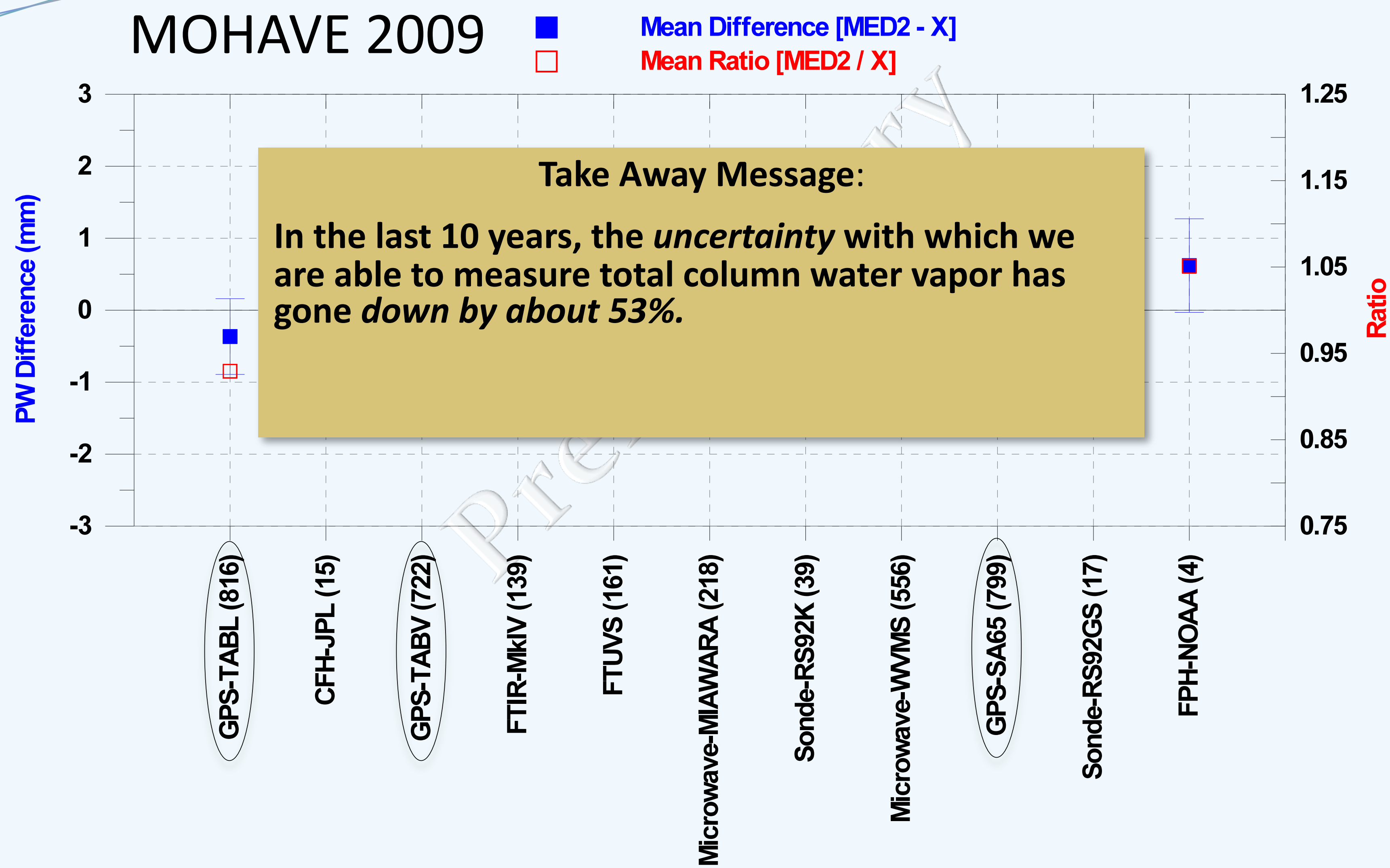


Take Away Message:

In the last 10 years, the *uncertainty* with which we are able to measure total column water vapor has gone *down by about 53%.*

GPS-Met in NOAA

NOAA Mission:
To understand and predict changes in Earth's environment and conserve and manage coastal and marine resources to meet our nation's economic, social, and environmental needs

Climate Goal:

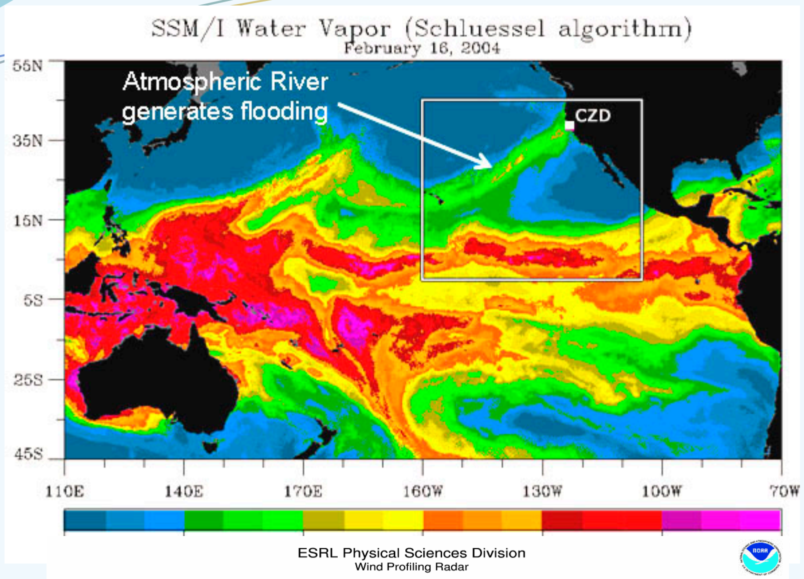
Weather & Water Goal:

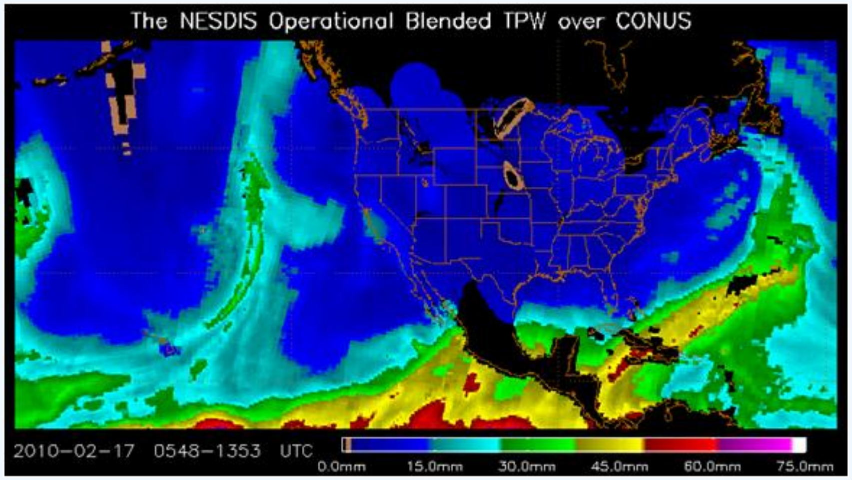
Commerce & Transportation Goal:

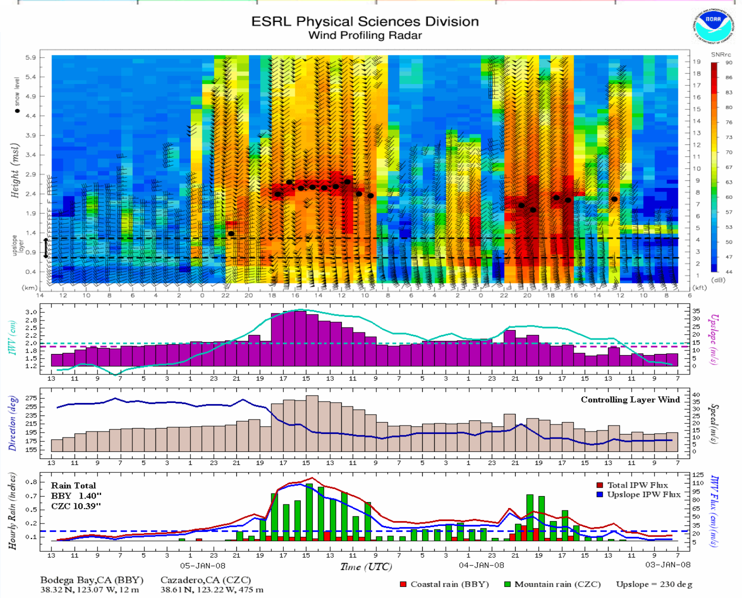
Satellites
Modeling & Observing Systems

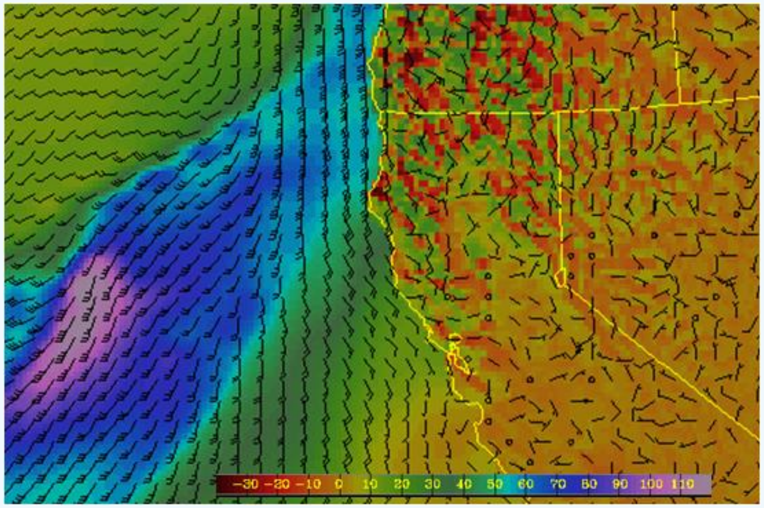
GPS-Met supports NOAA's Mission by providing reliable and accurate refractivity & moisture observations at low cost under all weather conditions.

Applications of GPS-Met



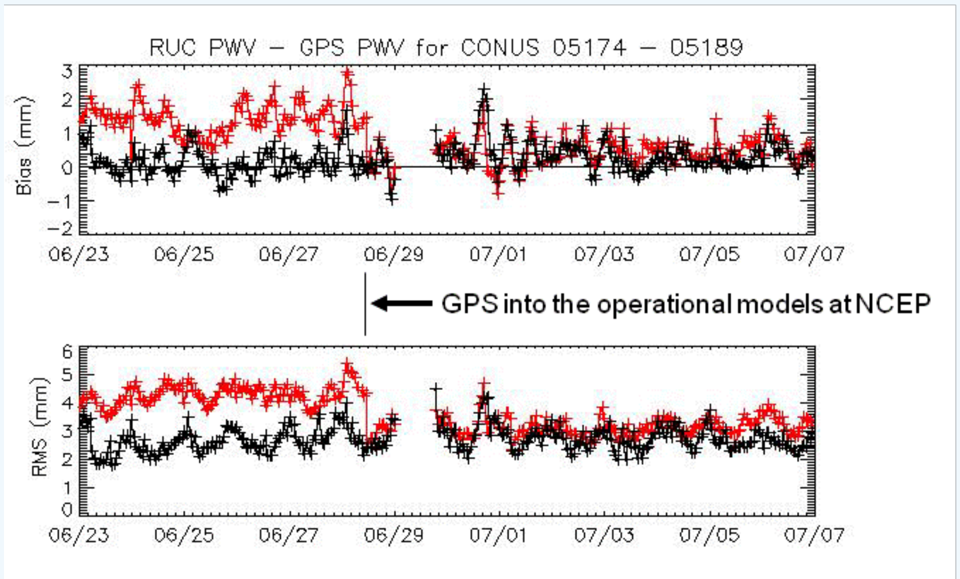






Example: NWP

GPS Water Vapor Measurements Enter Service in Operational RUC Weather Model on 28 June 2005



+ Operational Model
+ Research Model

Short-Range Forecast Impact from Assimilation of GPS-IPW Observations into the Rapid Update Cycle

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Smith, T.L., S.G. Benjamin, S.I. Gutman, and S.R. Sahm, 2007: **Short-range forecast impact from assimilation of GPS-IPW observations into the Rapid Update Cycle**. Mon. Wea. Rev., Vol. 135, No. 8, 2914–2930.

evident in 6- and 12-h forecasts. The impact of GPS-IPW data was also examined on forecasts from the more recent 20-km RUC, including a 1-h assimilation cycle and improved assimilation and physical parameterizations, now using real-time GPS-IPW retrievals available 30 min after valid time. In a 3-month comparison during the March–May 2004 period, 20-km RUC cycles with and without assimilation of GPS-IPW were compared with IPW for 3-, 6-, 9-, and 12-h forecasts. Using this measure, assimilation of GPS-IPW data led to the strongest improvements in the 3- and 6-h forecasts and smaller but still evident improvements in 9- and 12-h forecasts. In a severe convective weather case, inclusion of GPS-IPW data improved forecasts of convective available potential energy, an important predictor of severe storm potential, and relative humidity. Positive impact from GPS-IPW assimilation was found to vary over season, geographical location, and time of day, apparently related to variations in vertical mixing. For example, GPS-IPW has a stronger effect on improving RH forecasts at 850 hPa at nighttime (than daytime) and in cooler seasons (than warmer seasons) when surface moisture observations are less representative of conditions aloft. As a result of these studies, assimilation of GPS-IPW was added to the operational RUC run at NOAA/NCEP in June 2005 and to the operational North American Mesoscale model (also at NCEP) in June 2006 to improve their accuracy for short-range moisture forecasts.

1. Introduction

Observational tracking of the often rapidly evolving moisture field is an essential component of weather forecasting and numerical weather prediction (NWP). Short-range numerical weather forecast accuracy often suffers from inadequate observational definition of the three-dimensional moisture field because of its high spatial and temporal variability. Currently, three observation systems provide most atmospheric water vapor measurements: rawinsondes, surface stations, and satellites. Of these, only rawinsondes routinely provide full tropospheric moisture profiles but do so with only 12-h temporal resolution and varying degrees of accuracy and reliability (e.g., Turner et al. 2003). Surface measurements of dewpoint temperature convertible to relative humidity are available with high temporal resolution but are not highly correlated with upper-air moisture. Satellite infrared sounder measurements can-

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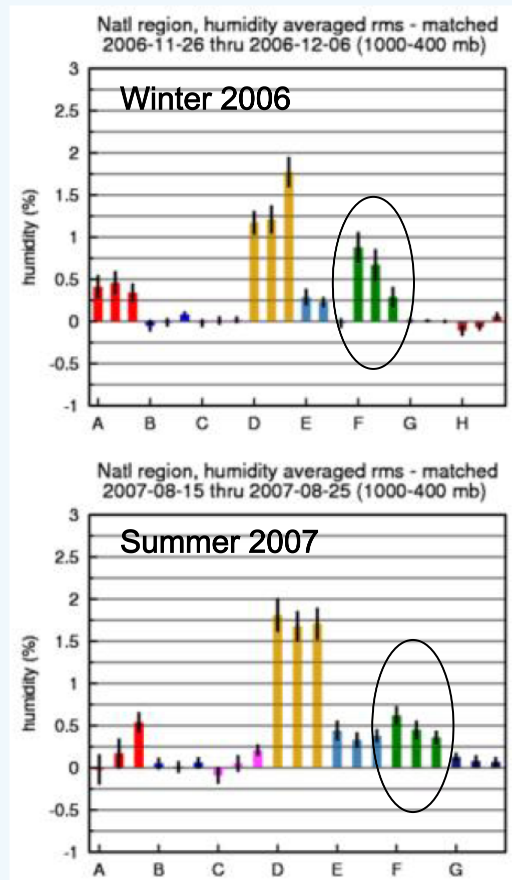
Example: NWP

Currently <300 stations in CONUS
Only 1-in-5 belong to NOAA/ESRL

Full Implantation of an Operational GPS-Met Network over CONUS = 800 stations

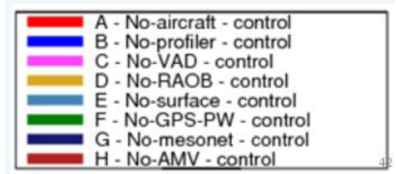
~ 200 will belong to NOAA/NWS

RUC RH Data Denial Experiments
2006-2007



Relative impact of different observing systems on NWP Fcsts as a function of time of year

#1: RAOB
#2: GPS
#3: Aircraft



Example: NWP

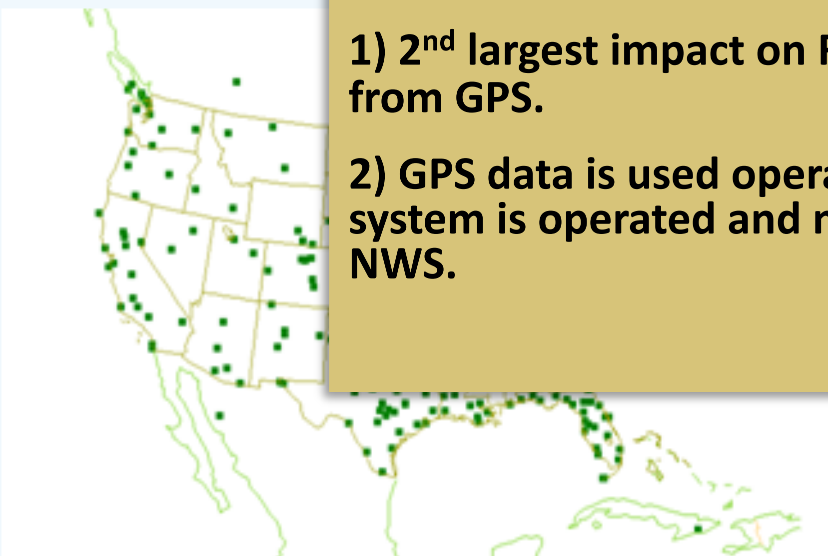
Currently <300 stations in CONUS
Only 1-in-5 belong to NOAA/ESRL

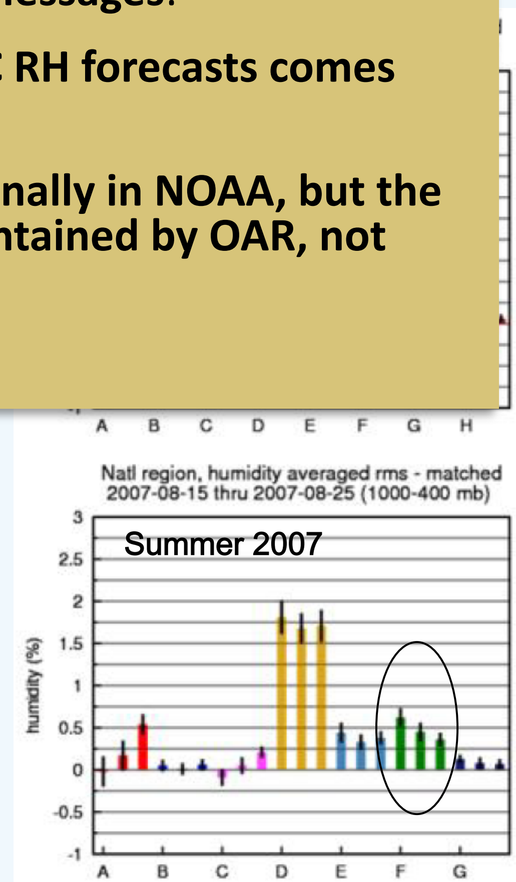
RUC RH Data Denial Experiments
2006-2007

Take Away Messages:

1) 2nd largest impact on RUC RH forecasts comes from GPS.

2) GPS data is used operationally in NOAA, but the system is operated and maintained by OAR, not NWS.





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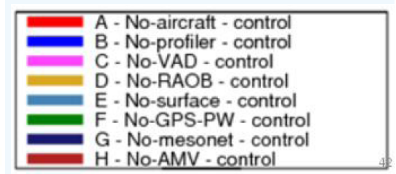
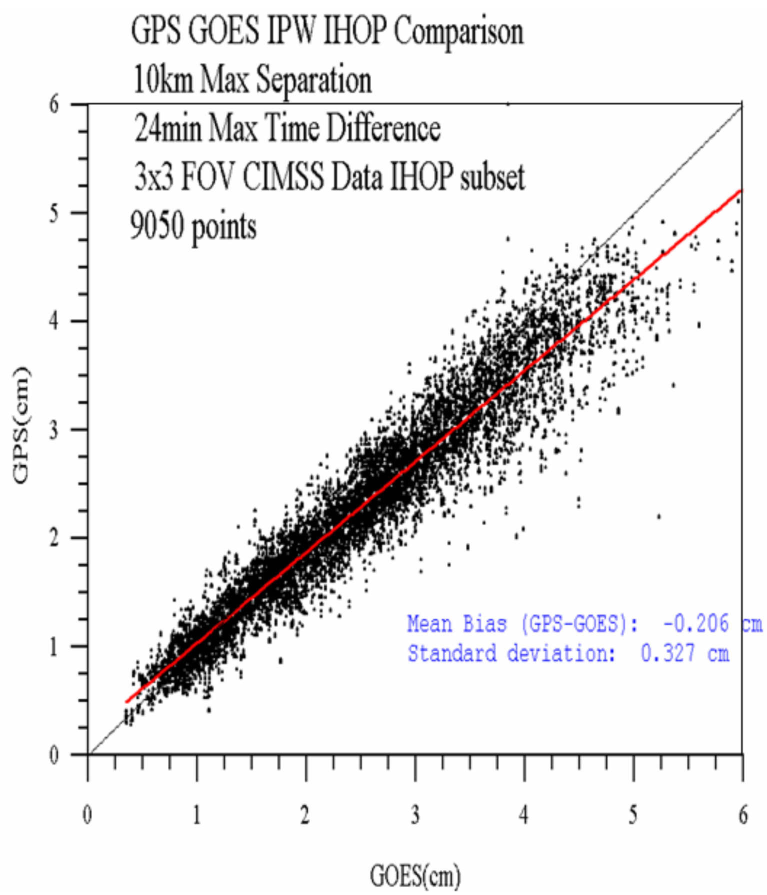


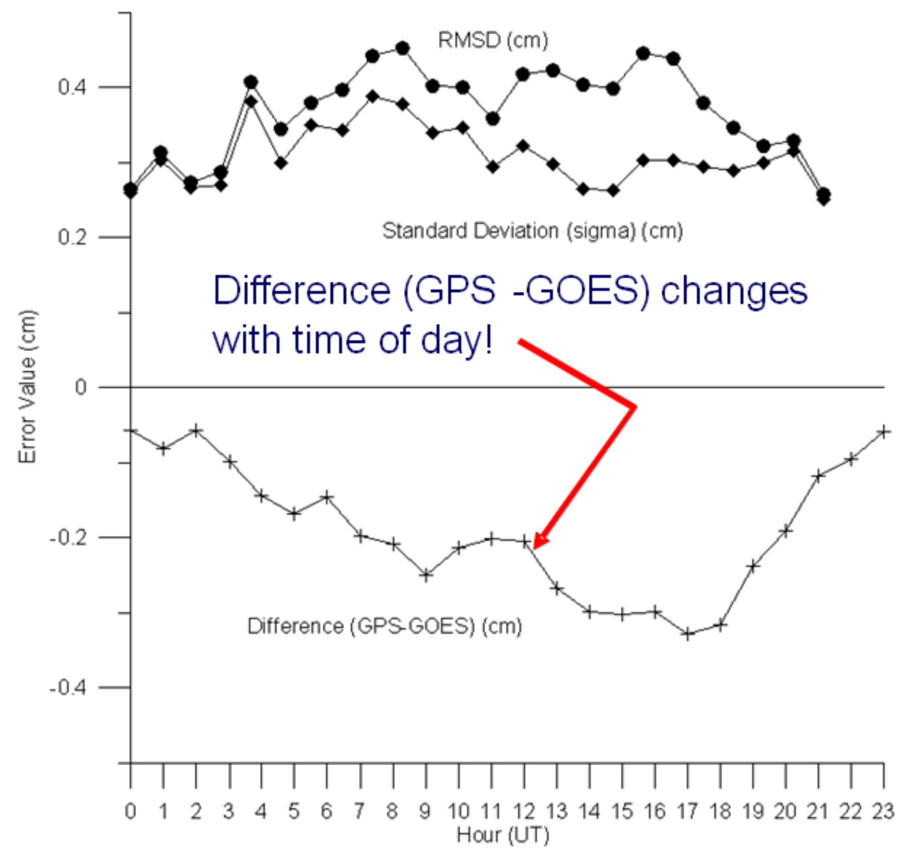
Full Implantation of an Operational GPS-Met Network over CONUS = 800 stations

~ 200 will belong to NOAA/NWS

Example: Satellite Cal/Val

Systematic differences between operational GOES East TPW products & GPS were detected in 2002.

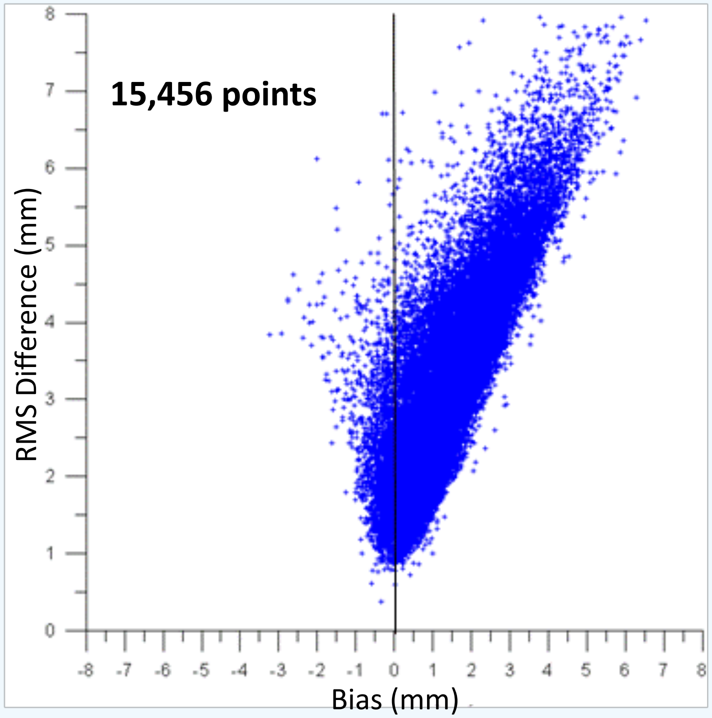




Example: Satellite Cal/Val

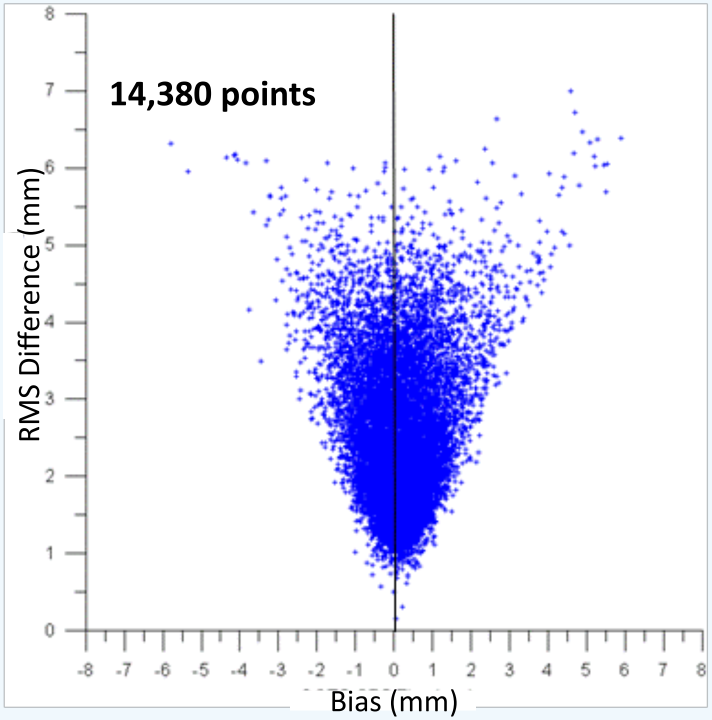
Systematic differences between operational GOES East & GOES West TPW products were detected in 2005.

Operational GOES East - GPS



Bias = 1.452 mm (GOES-East > GPS)
RMS = 3.244 mm

Operational GOES West - GPS

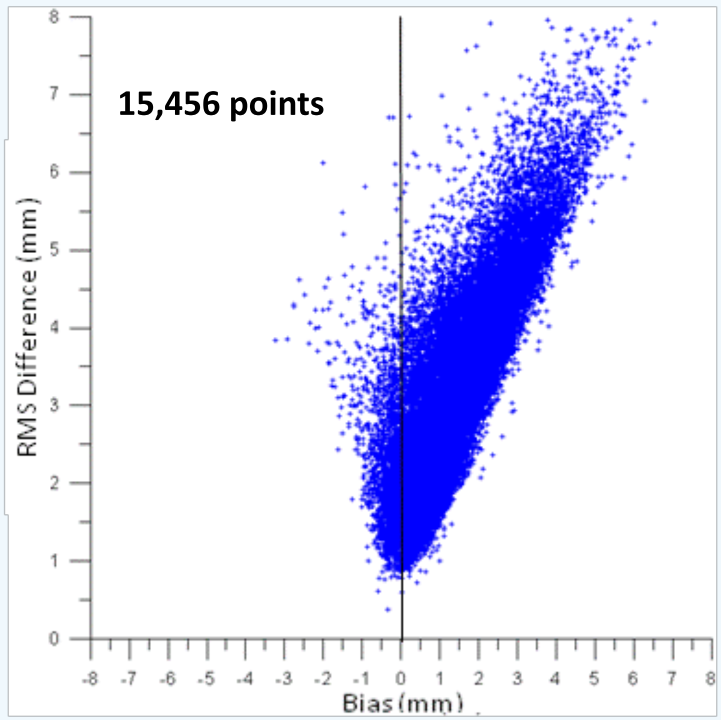


Bias = 0.299 mm (GOES-West > GPS)
RMS = 2.522 mm

Example: Satellite Cal/Val

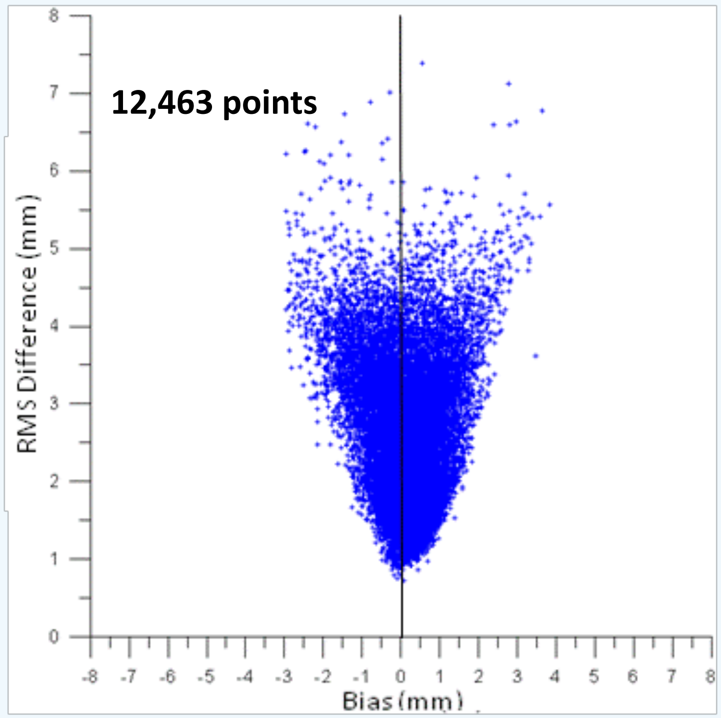
Significant improvements in experimental GOES East TPW products were demonstrated in 2008.

Operational GOES-East



Bias = 1.452 mm (GOES-East > GPS)
RMS = 3.244 mm

Experimental GOES-East



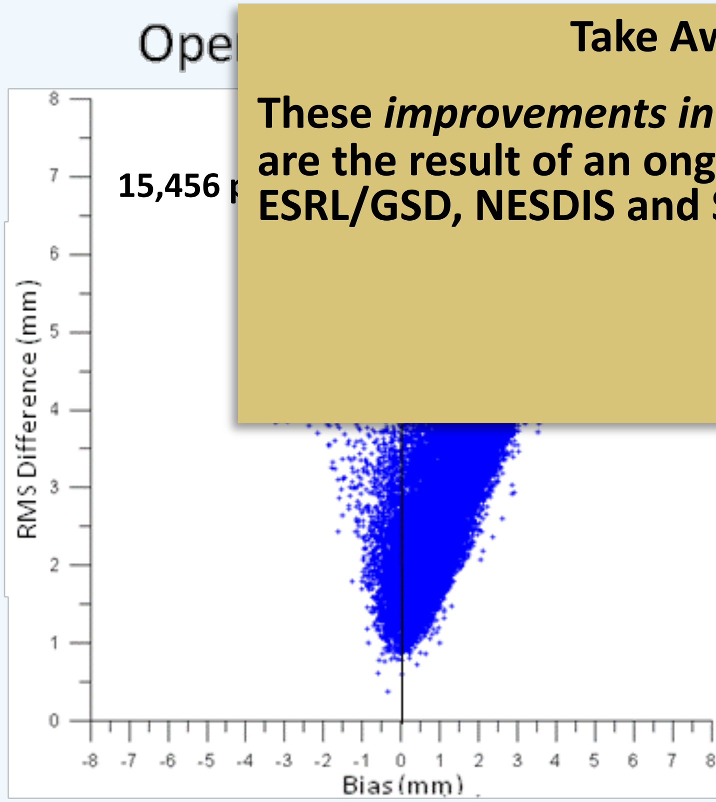
Bias = 0.149 mm (GOES-East > GPS)
RMS = 2.681 mm

Example: Satellite Cal/Val

Significant improvements in experimental GOES East TPW products were demonstrated in 2008.

Take Away Message:

These *improvements in GOES-EAST TPW retrievals* are the result of an ongoing collaboration between ESRL/GSD, NESDIS and SSEC @ U. Wisconsin.



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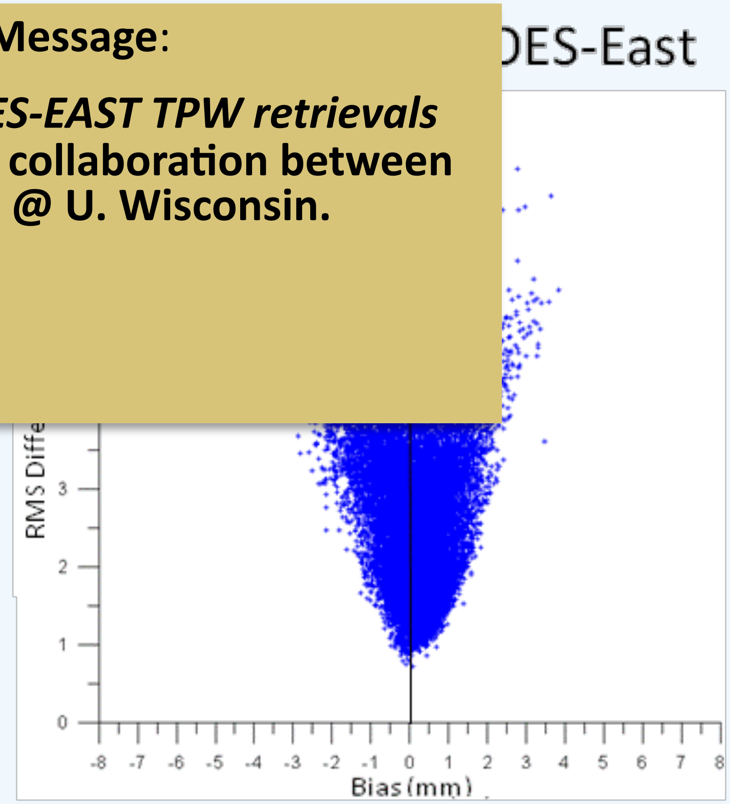

Bias = 0.149 mm (GOES-East > GPS)
RMS = 2.681 mm

Summary

- GPS TPW accuracy is sufficient to detect mm-level errors in TPU
- GPS data and products are used operationally:
  - data displayed on operational AWIPS workstations.
  - GPS data used by NWS to assess and QC operational NWS rawinsondes.
  - GPS data used by operational forecasters to improve forecast skill during severe weather events.
  - GPS observations are assimilated into almost all operational NCEP models.
- GPS-Met is ***ready, willing and able*** to transition from research into operations.

Looking Forward

- GPS will be installed at all GCOS Reference Upper-Air Network (GRUAN) Sites to verify *in situ* and remote sensing moisture soundings for ***climate monitoring***.
- GPS IPW estimates will be routinely made on ships in the open ocean to ***calibrate and validate*** satellite and aircraft measurements.
- GPS will be used to ***reduce uncertainty*** in monitoring ocean height levels by correcting satellite altimeter errors caused by mis-modeling tropospheric signal delays.
- GPS observations will be made at high altitude observatories around the world to place ***empirical constraints*** on moisture changes in the middle-upper troposphere.